

Setting a World Driving Record with Hydrogen



Livermore researchers demonstrate the extended driving range offered by a liquid-hydrogen-fueled hybrid car.

LAURENCE Livermore employees and visitors last January might have spotted a white Toyota Prius hybrid vehicle driving continuously around the square-mile site. The car was making history by setting a world record for the longest distance

driven on one tank of fuel in a vehicle modified to run on hydrogen.

In setting the distance record, a group of Livermore researchers took another step toward helping create a clean transportation system based on hydrogen.

The group made history with a prototype of a concept called cryogenic-compressed tanks. These superinsulated, high-pressure tanks contain extremely cold, liquid hydrogen instead of the room-temperature compressed hydrogen gas typically used in hydrogen test vehicles. (See the box on p. 13.)

The Prius, which has a combination electric motor and small internal combustion engine, traveled 1,050 kilometers (653 miles) on a tank containing 150 liters (almost 40 gallons) of liquid hydrogen. The overall fuel economy for the driving conditions used by the Livermore team was about 105 kilometers per kilogram of hydrogen, which is equivalent to about 65 miles per gallon of gasoline. Coincidentally, 1 kilogram of hydrogen has about the same energy content as 1 gallon of gasoline.

“One thousand kilometers is a very long range for a hydrogen vehicle because the fuel is difficult to store compactly,”

says Salvador Aceves, who leads the Energy and Environment Directorate’s Energy Conversion and Storage Group. Chief technician Tim Ross says, “The range we achieved is better than we expected. We originally anticipated the car would travel about 800 kilometers (500 miles) on 10 kilograms of hydrogen.” He describes the group’s Prius as a “moving hydrogen-storage technology test bed.”

For more than a decade, the Livermore group has been working on alternative, environmentally clean energy technologies for transportation, including hydrogen-fueled vehicles. Members include Aceves, Ross, Gene Berry, Vern Switzer, Francisco Espinosa-Loza, Dan Flowers, Rich Fairchild, Jim Fugina, Fernando Luna, Mark McCuller, Andrew Weisberg, Blake Myers, and Brian Kelly. The group has expertise in mechanical engineering, physics, analytical chemistry, hydrogen storage and usage, combustion

engineering and modeling, and energy modeling.

The team previously developed a conceptual design for a hydrogen hybrid vehicle that combines a small piston engine with an electrical generator. (See *S&TR*, July 1995, pp. 26–27.) Other projects have included the development of advanced analysis capabilities for high-efficiency, clean engines and a large engine for stationary energy generation. (See *S&TR*, December 1999, pp. 4–10; April 2004, pp. 17–19.) The team has collaborated with companies such as Ford, BMW, General Atomics, Caterpillar, Navistar International, and Cummins.

The Livermore work, sponsored by the Department of Energy’s (DOE’s) Office of Energy Efficiency and Renewable Energy, is part of DOE’s National Hydrogen Storage Project to demonstrate advanced hydrogen-storage materials and designs. The project is a component of President George W. Bush’s Hydrogen Fuel Initiative launched in 2003 as well as the DOE Advanced Energy Initiative of 2006.



A team of Laboratory researchers converted a Toyota Prius to run on a Livermore-designed hydrogen storage system. Left to right: Gene Berry, Francisco Espinosa-Loza, Salvador Aceves, Tim Ross, and Vern Switzer. (Not shown: Dan Flowers, Rich Fairchild, Jim Fugina, Fernando Luna, Mark McCuller, Andrew Weisberg, Blake Myers, and Brian Kelly.)

Dependence on Fossil Fuels

The U.S. transportation sector is almost 100 percent dependent on fossil fuels. Because transportation accounts for more than two-thirds of the petroleum consumed daily in the nation, DOE’s hydrogen program focuses primarily on developing hydrogen technology for this sector.

Today, more than 500 hydrogen-powered cars are on the road worldwide. Most use internal combustion engines, which are converted to run on hydrogen with only minor modifications to the fuel-injection system. When burning hydrogen, they generate zero greenhouse gases and only small amounts of nitrogen oxides.

A more energy-efficient use of hydrogen would entail replacing the internal combustion engine with fuel cells and an electric motor. In fuel cells, hydrogen reacts with oxygen, producing

electricity to power the vehicle. Water vapor is the only emission. Although research is progressing at a fast pace, fuel cells are still quite expensive.

Hydrogen Offers Big Advantages

Many energy scientists are optimistic that hydrogen-burning vehicles will not only help the nation's energy consumption but also curb the release of greenhouse gases such as carbon dioxide. "Increasing use efficiency is an important first step but may not be enough for steep reductions in petroleum dependence and greenhouse-gas emissions," says Aceves. "We ultimately need to advance to a carbonless energy system using hydrogen fuel."

Aceves says, "Hydrogen-fueled vehicles enable carbonless transportation. We can't collect all the greenhouse gases from the tailpipes of cars and trucks. Instead, we can make hydrogen from natural gas or coal and sequester underground the greenhouse gases that are generated during production." A better choice, he says, is to use nuclear power or

renewable energy (wind, solar, or biomass) to drive electrolysis, which splits water into hydrogen and oxygen and does not generate any pollutants.

Most prototype hydrogen vehicles use compressed hydrogen stored at room temperature and high pressure (35 to 70 megapascals or 350 to 700 atmospheres). Despite hydrogen's stellar fuel efficiency, it is difficult to store compressed hydrogen in the large quantities needed to provide the driving range achieved by gasoline- and diesel-powered vehicles. The energy density of compressed hydrogen at 35 megapascals is only about one-twelfth that of gasoline. As a result, hydrogen cars use large high-pressure tanks often located in the trunk. According to DOE studies, these cars have a driving range of up to 300 kilometers, adequate for around town or most commutes but not for a long trip.

Cooling Is Key

Like all gases, compressed hydrogen can be stored more compactly at colder

temperatures. Pressurized hydrogen at 35 megapascals becomes twice as dense when cooled from ambient temperature to -150°C . Cooling it further to -210°C (close to that of liquid nitrogen) triples the energy density. Cooling hydrogen also lowers the potential risk of a sudden tank rupture, increasing the safety factor.

The team has focused on liquid hydrogen (-253°C) because it does not require a high-pressure tank, and it takes up one-third the volume of compressed hydrogen at room temperature. Liquid hydrogen can also be delivered in large quantities (up to 4,000 kilograms) cost-effectively by truck. Finally, liquid hydrogen is relatively safe to store in compact, lightweight, low-pressure containers that depend on superinsulation instead of refrigeration to keep the hydrogen extremely cold.

Livermore researchers are experienced at using liquid hydrogen in research projects. For example, physicists used liquid hydrogen in targets for shock-compression experiments to achieve

Most Abundant Element in the Universe

With one proton and one electron, hydrogen is the first element on the periodic table and the lightest, most abundant element in the universe. Invisible and odorless, hydrogen is not toxic or corrosive.

Hydrogen does not exist naturally on Earth in its pure form. It must be produced from water using a source of energy such as electricity, heat, or another fuel (for instance, natural gas or coal). The most widespread production method reacts natural gas with steam to produce hydrogen and carbon dioxide. However, this method begins with a fossil fuel and therefore generates greenhouse gases. One approach to managing the greenhouse-gas problem is to immediately sequester the gases underground. Alternatively, nuclear or renewable energy (wind, solar, or biomass) could be used to electrolyze water.

Hydrogen has the highest combustion energy by weight of any fuel. Burning 1 kilogram of hydrogen produces 2.6 times more energy than 1 kilogram of gasoline. However, gaseous hydrogen pressurized to 35 megapascals needs about 12 times the volume of gasoline to produce the same amount of energy. Widespread development of vehicles running on compressed hydrogen gas has been slow because of this low energy density.

Hydrogen has been safely used as a fuel since the 1950s by the National Aeronautics and Space Administration in the U.S. space program and as a feedstock in the chemical industry and for oil refineries. Hydrogen suffers from many misperceptions about its safety, especially since the explosion of the hydrogen-fueled Hindenburg dirigible in 1937. However, the fire that destroyed the Hindenburg was caused by an electrical charge that ignited the flammable coating.

California state government leaders have been among the strongest supporters of using hydrogen as a transportation fuel. "California is becoming the capital of hydrogen research," says Livermore's Gene Berry, an engineer and energy analyst. The goal of the California Hydrogen Highway Network initiative is to support a transition to a hydrogen-based transportation economy. The initiative has a goal of 50 to 100 hydrogen-fueling stations (about 24 have already been built) and 2,000 hydrogen-powered vehicles on the road by 2010. One plan is to locate liquid-hydrogen filling stations near freeways because drivers on long trips would choose that form of hydrogen for its longer range.

For more information on the California initiative, see <http://hydrogenhighway.ca.gov/>.

hydrogen's metallized state for the first time. (See *S&TR*, September 1996, pp. 12–18.) Aceves's group is using the same liquid-hydrogen storage and pumping facility that the physicists installed for their shock experiments.

Among the automotive companies, BMW has spearheaded the use of liquid hydrogen in automobiles. BMW is leasing 100 dual-fuel luxury V-12 automobiles that run on both gasoline and hydrogen. The driver switches operation between gasoline and the liquid hydrogen stored in a low-pressure tank behind the rear seat.

A major drawback to using liquid hydrogen is the significant electricity required to liquefy it (about equal to 30 percent of the energy content of the hydrogen molecule). In addition, liquid hydrogen is extremely sensitive to heat; it expands significantly when warmed only a

few degrees. As a result, vehicles that use low-pressure tanks are usually not filled to maximum capacity and must have a system to release some of the hydrogen vapor that accumulates in the tank when the car is not driven for several days. In a parked car, the tank pressure can build until it surpasses the service pressure (the pressure for which the tank was built). At this point, the hydrogen is released through a safety valve from the vessel. A driver leaving his or her car at the airport for a long time, for example, might find the tank empty upon returning. Drivers whose cars also run on gasoline, such as the new dual-fuel BMWs, would not have this problem because they could use the gasoline fuel.

Alternatively, a high-pressure tank could be used for hydrogen-fuel storage. While researching hydrogen car concepts nearly 10 years ago, the Livermore team designed a high-pressure tank for low-temperature hydrogen that was safe, compact, lightweight, and superinsulated. (See *S&TR*, June 2003, pp. 24–26.) The tank comprises an high-pressure inner vessel made of carbon-fiber-coated aluminum, a vacuum space filled with numerous sheets of highly reflective plastic, and an outer jacket of stainless steel. (See the box on p. 15.)

The Livermore design allows a driver to refuel with liquid hydrogen or compressed hydrogen gas, or with hydrogen at any temperature and pressure in between. If the insulated pressure vessel is fueled with liquid hydrogen, it goes a long way toward solving the problems associated with low-pressure tanks such as having to vent the buildup of hydrogen gas. Because the tank is built to withstand high pressures, hydrogen gas that accumulates must reach a much higher temperature than in low-pressure tanks before venting is required. Livermore tests have shown that under normal use, evaporative losses would be reduced and drivers would not be at risk of being stranded without fuel.

A driver could refuel most of the time with room-temperature compressed

hydrogen, likely purchased at a lower cost, and also have the flexibility of using liquid hydrogen at any time to greatly extend the driving range. In this way, a driver could use room-temperature compressed hydrogen for short trips and liquid hydrogen for longer trips. "Drivers would fill with liquid hydrogen only when they chose to extend their driving range," says Aceves.

First Design Makes the Cover

The first-generation design of the Livermore storage system was featured on the cover of the February 2002 issue of *Mechanical Engineering*. The 25-megapascal tank held 135 liters (about 36 gallons) of hydrogen and measured about the size of a water heater. "At that time, we were less concerned about the tank's external size than proving the technology worked," says Ross.

In 2004, the tank was installed in the back of a Ford Ranger pickup provided by SunLine Transit Agency of Riverside County, California. The project was funded by DOE and California's South Coast Air Quality Management District. The team drove the truck about 480 kilometers (300 miles) around the Laboratory using both compressed and liquid hydrogen. The truck was returned to SunLine Transit Agency, where it underwent a year of testing. Aceves says, "We proved that our design works safely with both compressed and liquid hydrogen."

Building on the experience gained with the first tests using the Ranger, the team improved the storage system's weight, insulation, fuel capacity, and external size. The second-generation pressure tank is smaller yet holds more fuel because of its streamlined insulation. The goal is to reduce the tank's size even further and still achieve a driving range of more than 480 kilometers (300 miles).

In July 2006, the Laboratory acquired a Prius, which had been converted to run on hydrogen by Quantum Fuel Systems Technologies Worldwide, Inc., of Irvine, California. "We chose the Prius because



Francisco Espinosa-Loza (left) and Tim Ross lower the inner pressure vessel, insulated with reflective sheets of aluminum and plastic, into the outer stainless-steel vacuum jacket.

Tank Can Take the Heat—and the Cold

The Livermore liquid-hydrogen storage tank consists of an inner pressure vessel and an outer vacuum jacket. The inner vessel is made of aluminum coated with carbon fibers for high strength. It was custom-fabricated by Structural Composites Industries of Pomona, California. Once the inner pressure vessel arrived at Livermore, technicians wrapped it in 50 layers of highly reflective metallized plastic. The inner vessel was then slid into a stainless-steel vacuum jacket fabricated by a vendor to Livermore specifications. The inner vessel was centered inside the outer jacket using several small fiberglass rings. The two-part tank was then welded shut, and the air between the two vessels was pumped out to create a vacuum.

The vacuum minimizes the conduction of heat between the outer steel jacket and the inner pressure vessel, which would cause liquid hydrogen to evaporate quickly. In addition, the multiple layers of reflective material almost eliminate heat transfer from radiation, much like a Thermos bottle.

The outer steel jacket has cutouts for thermocouples and sensors to measure pressure, temperature, and the fuel level within the inner vessel. In addition, the system is equipped with two safety devices to prevent catastrophic failure in case of overpressure. The first device is spring actuated and can open and reseal to minimize the loss of hydrogen. The second device is a backup rupture disk that once opened, stays open. The rupture disk would be triggered if the tank was in a fire and the pressure rose too fast for the spring-loaded valve to vent it.

The storage tank has undergone numerous tests to demonstrate its safety and reliability. The tests follow procedures specified by the U.S. Department of Transportation, the Society of Automotive Engineers, and the International Organization for Standardization. In every case, the tank met the test criteria. The tests were conducted both at Livermore test facilities and at outside private laboratories certified by the Department of Transportation. Some of the tests focused on the inner aluminum-composite vessel, and other tests evaluated the entire tank.

One test involved 900 high-pressure cycles and 100 low-temperature cycles. During a high-pressure cycle, the pressure is increased from ambient pressure to the service pressure (35 megapascals) and then reduced back to ambient pressure. During a temperature cycle, the inner vessel is filled with liquid nitrogen and then emptied. The cycles are alternated, with nine pressure cycles being run followed by a temperature cycle. This sequence is repeated 100 times. The test is equivalent to more than 480,000 kilometers of driving with a high-efficiency vehicle. The vessel withstood the cyclic tests without evidence of damage, distortion, or leakage.

Many other tests were performed, including cycling 5,000 times from zero to service pressure at different temperatures and humidities. In another test, the inner vessel was burst-tested after being cycled at cryogenic temperature. The inner vessel was also pressurized with gaseous nitrogen to service pressure and shot with a 0.30-caliber armor-piercing projectile from 15 meters. The vessel remained in one piece when pierced by the bullet.

The entire tank was also placed in a bonfire, and the pressure relief device fully vented the gas. In another test, the tank was subjected to a drop from 3 meters while empty and from 10 meters filled with liquid nitrogen. In both instances, the tank remained intact.

In addition to these tests, the inner pressure vessel was analyzed with finite-element computer software. The results indicated that repeated cryogenic and high-pressure cycling is unlikely to damage the vessel, which is in agreement with experimental results.



In one test, the tank was placed in a bonfire for 20 minutes. The pressure-relief device fully vented the gas, as designed.



In a test of strength, the tank was dropped from a height of 3 meters while empty and from 10 meters (shown) filled with liquid nitrogen. The tank successfully contained the liquid nitrogen for the required 60 minutes.



Left to right: Mark McCuller, Jim Fugina, Francisco Espinosa-Loza, and Tim Ross worked on the first-generation design of the Livermore hydrogen storage system, which was installed in the back of a Ford Ranger pickup.



Vern Switzer (left) and Tim Ross check the pressure on the inner vessel that holds hydrogen of any temperature.

it was energy-efficient and required only a small tank of liquid hydrogen,” says Aceves. The Prius was selected because Quantum was already converting about 40 of the cars for use in cities in the Los Angeles area.

The modified Prius arrived with two room-temperature compressed hydrogen tanks rated at a pressure of 34 megapascals. The tanks could store a total of 1.8 kilograms of compressed gaseous hydrogen, enough to travel about 145 kilometers (90 miles). Livermore researchers removed the tanks and installed their second-generation tank system, relocating the Prius’s electric motor batteries to underneath the car.

“We first performed tests using a combination of compressed hydrogen and liquid hydrogen in the tanks. Then for the continuous test drive on one full tank, we used all liquid hydrogen,” says Ross.

The circuit testing of the Prius took place over a two-week period in January 2007, with group members taking turns driving on a continuous 5-kilometer (3-mile) circuit on the Livermore site. Drivers recorded operating parameters, including driving distance, fuel use and pressure, fuel temperature, and fill level. The test drive was conducted at 40 to 56 kilometers (25 to 35 miles) per hour because of site speed limits. Aceves estimates that under more realistic driving conditions, the Prius would average about 88 kilometers (55 miles) per kilogram instead of the 105 kilometers (65 miles) per kilogram achieved at the low speeds.

One Small Step

Despite the resounding success of the Livermore system, Aceves cautions that a great deal more research is needed before the design is ready for mass-produced

hydrogen vehicles. The team is collaborating with industry to design more compact vessels with improved thermal endurance. In addition, the team has had discussions with both domestic and foreign automakers. A third-generation tank design is planned, with even greater performance expected.

The Livermore team is playing an important role in making possible both clean and sustainable transportation fueled by the simplest element in the universe.

—Arnie Heller

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